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Multiple-attribute Decision Making for an Energy Efficient Facility Layout Design

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Abstract

Due to restricted energy resources, energy efficiency which was always ignored over the past decades becomes a significant challenge for many factories. Therefore, it is necessary to integrate energy relevant criteria with traditional criteria in the layout planning phase. The proposed approach employs a hybrid approach which integrates analytic hierarchy process (AHP) and preference ranking organization methods for enrichment evaluations (PROMETHEE) with the purpose of solving a facility layout problem (FLP). The AHP is used to determine the weights for each criterion and PROMETHEE is applied to get the final ranking. Finally, a case study is used to validate the proposed approach.

Keywords: Decision making; energy efficiency; facility layout planning

1. Introduction

Manufacturing companies share the common goals towards cost effectiveness, energy efficiency and sustainability. In the age of energy shortage and energy price rise, energy efficiency becomes a significant challenge for many factories. Therefore, it should be considered as an essential factor in early planning phase. Furthermore, building an energy efficient facility planning is not only a problem of cost reduction, but also a great contribute to the environmental protection [1].

The traditional FLP generally focuses on quantitative criteria such as shape ratio, material handling cost and space demand, as well as the qualitative criteria such as flexibility and quality. However, due to the trends of energy shortage and energy price rise, energy relevant criteria should be combined with the traditional criteria in the facility layout planning phase.

Most FLP have several optimization objectives which have different units and conflicting features. In order to acquire the best solution for all involved objectives, many multi-objective optimization approaches which finally obtain an optimal solution set instead of single optimal solution [2, 3], have been developed. Under this condition, the layout designers should choose a best solution according to the practical situation and their preferences from the solution set. However, layout decision making is always a multiple-attribute decision making (MADM) problem. Hence, the evaluation of FLP alternatives is always difficult and time consuming because of its inherent multiple attribute features.

Although the layout evaluation plays an essential role in the process of designing an effective facility layout, there are few researches in this field. Literature [4] uses various computer-aided layout approaches to obtain several layout alternatives and employs AHP to evaluate them considering with a set of design criteria. AHP is able to provide weights for qualitative layout evaluation criteria, but many quantitative criteria are difficult to be distinguished with its 9-point scale. Therefore, many studies use AHP with other decision making methods. Yang integrates AHP and data envelopment analysis (DEA) to solve plant layout design problem [5]. In addition, fuzzy-AHP and technique for order preference by similarity to ideal solution (TOPSIS) are combined to

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select the best layout from layout alternatives in literature [6]. In literature [7] grey relational analysis is applied to solve the multiple attribute layout decision making problems. However, energy relevant criteria are always ignored in the decision-making process. Furthermore, all above mentioned methods make the evaluations by using same preference function which may affect the correctness of the final decision due to the various features of criteria.

In this paper, a multiple-attribute decision making approach is presented to solve the facility layout decision making problem considering with both traditional layout criteria and energy relevant criteria. It integrates both advantages of AHP and PROMETHEE. The AHP is applied to analyze the structure of the facility layout evaluation problem, and to obtain the weights for each criterion. Based on the results of AHP, PROMETHEE then is applied to get the final ranking by using different preference function for each criterion according to their characteristics.

The following parts of this paper are organized as follows: section 2 represents the proposed approach briefly. In section 3, a case is applied to validate the proposed approach. Furthermore, a sensitivity analysis is performed. Finally, the main conclusions and future researches are summarized in section 4.

2. The hybrid decision making approach

In this section, AHP and PROMETHEE are briefly introduced. Then the hybrid approach is proposed to assist the layout decision making process.

2.1. AHP

AHP developed by Saaty (1980) provides a method to decompose the complex problem into a hierarchy of sub-problems which can be evaluated and handled more easily and rationally [8]. Moreover, AHP makes it possible to quantify the experiences of experts and to integrate those quantified experiences to the decision making process. Especially, when the structure of the object is complex and the data is missing, such quantified experiences are extremely valuable.

The AHP involves four steps [9, 10]:

- Developing a hierarchy structure. A complex decision problem is analyzed and a hierarchy of interrelated decision elements is formed. The hierarchy of AHP has at least three levels: the global goal is at the top, in the middle are the multiple criteria and the alternatives are at the bottom.
- Comparing the alternatives and the criteria. The data are collected and corresponded to the hierarchic structure. The pair comparison is applied to determine the relative importance of the criteria within each level according to their influences to the level above. The pairwise comparisons are quantified according to the nine-point intensity of importance scale [9].

  Assume that $C=\{C_j|\ j=1, 2, \ldots, n\}$ is the set of criteria. The results of the pairwise comparison among n criteria can be summarized in an $n*n$ evaluation matrix A. Each element a_{ij} $(i, j=1, 2, \ldots, n)$ in the evaluation matrix is the quotient of weights of the criteria.

$$A=(a_{ij}),\quad i,j=1,\ldots,n. \tag{1}$$

- Normalizing the evaluation matrix and finding the relative weights. The relative weights are acquired by the right eigenvector (w) corresponding to the largest eigenvalue (λ_{max}):

$$Aw=\lambda_{\max}w \tag{2}$$

- Evaluating the consistency of the matrix. The consistency index (CI) can be described as follows:

$$CI=(\lambda_{\max}-n)/(n-1) \tag{3}$$

  The final consistency ratio (CR) which can be used to evaluate whether the evaluations are sufficiently consistent or not, is calculated by CI and the random index (RI) as follows:

$$CR=CI/RI \tag{4}$$

  If the value of CR is larger than 0.1, the procedure should be repeated to improve the consistency.

2.2. PROMETHEE

The PROMETHEE method was firstly proposed by Brans (1985) [11]. The method uses outranking relation between pairs of alternatives to solve problems which have a finite alternatives and are needed to be sorted considering with conflicting criteria and different units. Unlike other ranking methods which apply the same evaluation scale and preference function in the evaluation process, the PROMETHEE usually uses different preference functions to define different decision attributes according to their different features [11, 12].

When a pair of alternatives (a, b) is compared, a preference function is used to express the difference between the two alternatives in terms of a preference degree range [0, 1].

Usually, two PROMETHEE methods [9] can be employed to solve the evaluation problems: PROMETHEE I and PROMETHEE II. Compared to

PROMETHEE I that provides a partial ranking of alternatives, PROMETHEE II offers a complete ranking from the best alternative to the worst one. Therefore, PROMETHEE II is chosen in the hybrid decision making approach.

The procedure of PROMETHEE II is constituted by four steps [9, 11, 12]:

- Calculating the deviations based on compared two alternatives with respect to *j*th criterion:

$$d_j(a,b) = f_j(a) - f_j(b) \quad j = 1,2,...,k. \tag{5}$$

where *j* denotes the *j*th criterion, *k* stands for the finite number of criteria.

- Applying the preference function:

$$P_j(a,b) = F_j[d_j(a,b)] \qquad j = 1,2,...,k \tag{6}$$

$$0 \le P_j(a,b) \le 1 \qquad j = 1,2,...,k \tag{7}$$

where $P_j(a, b)$ expresses the preference of alternative *a* with regarding to alternative *b* on the *j*th criterion.

- Calculating a global preference index. The overall preference index of alternative *a* over alternative *b* is denoted as:

$$\pi(a,b) = \sum_{j=1}^{k} w_j P_j(a,b) \quad j = 1,2,...,k \tag{8}$$

where w_j represents the weight of the criterion *j*.

- Calculating the outranking flows. The outgoing flow Φ^+ which expresses the outranking character of alternative *a* (how *a* dominates all the other alternatives) and the incoming flow Φ^- which indicates the outranked character of alternative *a* (how is *a* dominated by all the other alternatives) can be represented as follows:

$$\phi^+(a) = \sum_{x \in A} \pi(x,a) \tag{9}$$

$$\phi^-(a) = \sum_{x \in A} \pi(a,x) \tag{10}$$

where *A* denotes the alternative set.

The net flow $\Phi(a)$ which is defined by equation (11) expresses the overall preference degree of alternative *a*. Higher value of $\Phi(a)$ means a better performance of alternative *a*.

$$\phi(a) = \phi^+(a) - \phi^-(a) \tag{11}$$

2.3. The hybrid decision making approach

The hybrid approach of facility layout decision making, which integrates AHP and PROMETHEE II includes five steps, is displayed in the Fig.1:

- Step 1: Data gathering:

Firstly, the layout alternatives are obtained from a Matlab-based multi-objective optimization approach to generate pareto-optimal set with considering both energy relevant criteria and traditional layout criteria. Afterwards, the criteria for layout evaluation are determined. The decision making hierarchy structure is also established with the chosen layout alternatives. Finally, the criteria and hierarchy structure are checked.

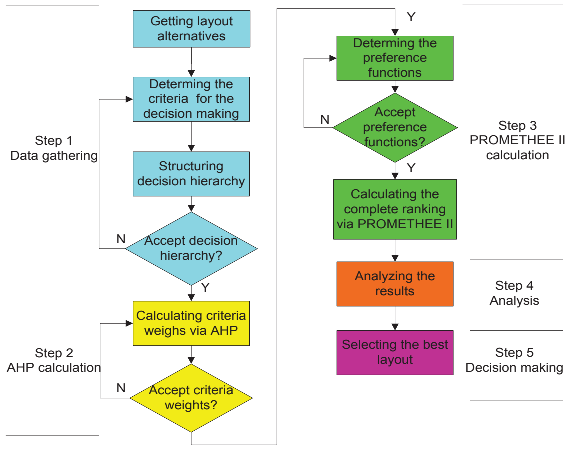

Fig. 1. Scheme of the proposed approach.

The proposed decision hierarchy structure contains three layers: In the first layer, the global goal of the decision making approach is confirmed as "selecting best layout". The layer below is the criteria layer which is consisted by determined decision criteria. Here, the energy relevant criterion is considered with other traditional layout criteria. The layout alternatives are on the bottom of the hierarchy.

- Step 2: AHP calculation:

In this step, individual pairwise comparison is carried out in the layout evaluation process. The weights of decision criteria are obtained. Finally, the consistency of pairwise comparison evaluation is checked.

- Step 3: PROMETHEE calculation:

The layout alternatives are evaluated with respect to each decision criterion to form the evaluation matrix and different preference functions with determined threshold values are defined for different decision criteria according to their characteristics. Afterwards, the values of outgoing/incoming flow are calculated. Finally, the final complete ranking can be found.

- Step 4: Analysis:

The sensitivity analysis is implemented in the analysis step. The stability intervals of each criterion are calculated. Therefore, the influences of each criterion on the global goal are found.

- Step 5. Decision making:

Based on above mentioned results, the final decision is made and the best layout is chosen.

3. Case study

In this section, we use an expanding case study based on [13] to validate the correctness of the proposed approach. In a paint department, there are six ovens which have a great amount of energy consumption. In addition, workplaces for filler application, basecoat application and clearcoat application are included. The original layout design is displayed in the Fig.2.

Nowadays, because of the demand of enlarging production and the challenge of energy efficiency, a new plant will be invested. In this case, because of the energy policy and the trend of energy price rise, energy saving is regarded as a key objective in the process of facility layout design because of its long term effect on expense reduction and clime protection. At the same time, several traditional layout criteria will be taken into account. However, it is difficult to find the most suitable one among several layout alternatives which dominate each other in different attributes.

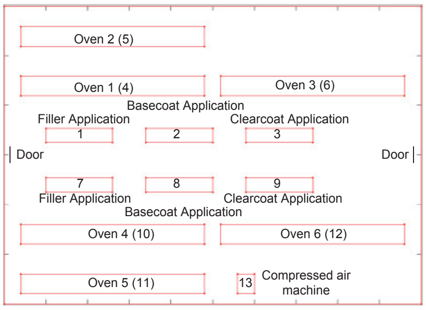

Fig.2. The original layout design.

According to the new requirements, three new layout designs namely layout 1, layout 2 and layout 3 (given in Fig.3) are generated by a Matlab-based multi-objective optimization approach considering with energy loss, transport performance and space requirement [14]. They all apply energy saving network to reduce the energy consumption. Besides, although layout 4 has the same layout as the original layout, it also employs energy recovery network, which means more investment while less energy consumption than the original layout.

Finally, the decision making criteria, namely space requirement (SR), investment for energy recovery network (Inv.), transport performance (TP), distance request (DR), energy saving (ES) and environment (Env.), are determined by the decision team.

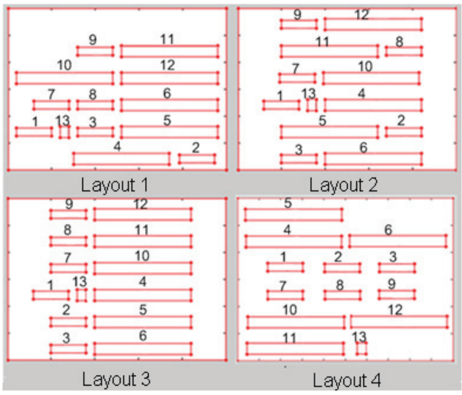

Fig.3. New layout designs.

The space requirement is equal to the needed minimum rectangle area. The investment for energy recovery network measures the costs for heat transfers and labour costs for installation. The transport performance is the sum of the products volume multiplying the rectangle distance between the output point of previous facility and input point of next facility. The distance request is measured by multiplying distance rating and distance between facilities. This requirement is related to satisfaction of environmental issues like noise, vibration, pollution or risks of fire or explosion. In addition, energy saving is used to measure the amount of energy consumption reduction of the new generated layout alternatives compared to the original layout design. Finally, the criterion environment is a qualitative criterion to evaluate the environmental performance of layout alternatives.

Afterwards, the weights for decision criteria are obtained by AHP calculation. The results of individual pairwise comparison are given in Table 1.

Table 1. Pairwise comparison matrix for decision criteria

Criteria	SR	Inv.	TP	DR	ES	Env.
SR	1	2	0.5	3	1	3
Inv.	0.5	1	0.5	3	0.5	3
TP	2	2	1	5	1	7
DR	0.33	0.33	0.2	1	0.2	1
ES	2	2	1	5	1	3
Env.	0.33	0.33	0.14	1	0.33	1

Afterwards, the results of consistency are given in Table 2. The final consistency ratio is 0.038<0.1, which means the assigned weights are consistent. Therefore, they can be applied in the further evaluation process. Besides, weights of criteria are shown in Table 3.

Table 2. Consistency of the pairwise comparison

λ_{max}	CI	RI	CR
6.236	0.047	1.24	0.038

In the step of PROMETHEE calculation, each layout alternative is evaluated with respect to the involve decision criteria, and the evaluation matrix is established as shown in Table 3.

Table 3. The evaluation matrix for layout selection

Criteria	SR	Inv.	TP	DR	ES	Env.
Unit	m^2	10^3 €	10^9 Kg*m/y	m	10^5 Kwh/y	-
Max/Min	Min	Min	Min	Max	Max	Max
Weights	0.193	0.134	0.300	0.053	0.265	0.056
Original design	1242	0	0.406	3612	0	4
Layout 1	1012	200	0.259	3872	8.446	3
Layout 2	972	150	0.176	3530	8.183	1
Layout 3	972	280	0.406	3522	9.201	5
Layout 4	1242	280	0.406	3612	7.863	4

Afterwards, different preference functions are assigned to various decision criteria according to their diverse features. The defined preference function and thresholds for each criterion are given in Table 4.

Table 4. Preference functions and thresholds

Criteria	Preference function	Thresholds	
		q	p
SR	V-shape	150	-
Inv.	V-shape	200,000	-
TP	V-shape	$0.2*10^9$	-
DR	Linear	100	250
ES	V-shape	200,000	-
Env.	Level	2	3

Then, the outgoing flow Φ^+, the incoming flow Φ^- and the net flow $\Phi(a)$ are calculated and shown in Table 5.

Based on the results of Table 5, the ranking of layout alternatives are obtained. Layout 2 which has minimum space requirement, minimum transport performance, is considered as the best layout alternative. Besides, because of the maximum distance request and balancing performance in other criteria, layout 1 is also preferred by decision makers and is regarded as the second best layout. For layout 3, although it has minimum space requirement, maximum energy saving and the best performance in environment, due to the bad performance in criteria investment and transport performance, it takes the third place in five layout alternatives. Besides, because of the poor performance in criteria space requirement, transport performance and energy saving, the original design and layout 4 are regarded as the two worst layouts.

Table 5. Results of PROMETHEE calculation

Layout	Φ^+	Φ^-	Φ
Original	0.133	0.552	-0.419
Layout 1	0.436	0.124	0.312
Layout 2	0.494	0.109	0.386
Layout 3	0.292	0.212	0.080
Layout 4	0.073	0.431	-0.358

However, the assigned weights are determined based on the experience of decision makers which is subjective and can easily be affected by different persons and environment. Therefore, it is necessary to analyse how the final ranking results are influenced by the fluctuation of criteria weights. For this reason, sensitivity analysis is employed to study the stability of the results obtained by the proposed approach.

One-dimensional sensitivity to the weights is widely applied to make the sensitivity analysis. By this method, if the analysis is studied on a given weight of a decision criterion, the ratios among other weights are remained constant [16]. Finally, the “stability intervals”, which means the value limits of the weight under study, are found. If the weight varies between the upper and under limits of the stability intervals, the final complete ranking will not be changed. The results of sensitivity analysis are shown in Table 6 and Fig.4.

Based on results of Table 6 and Fig.4, it is clear that the distance request has the greatest influence on the final layout ranking since it has smallest stability interval. In addition, under most conditions, layout 1 and layout 2 are ranked as the best two layout alternatives.

Table 6. Results of sensitivity analysis

Criteria	Weights	Interval	
		Min	Max
SR	0.193	0	0.618
Inv.	0.134	0	0.164
TP	0.300	0.157	1
DR	0.053	0	0.105

ES	0.265	0.215	0.533
Env.	0.056	0	0.149

According above mentioned to analysis, layout 2 is chosen due to its good performance among all considered criteria and its stability during the variation of the criteria weights.

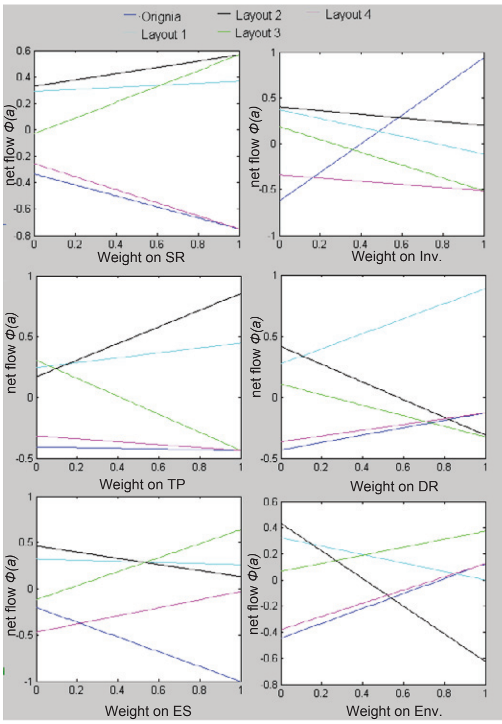

Fig. 4. Sensitivity analysis of the weights.

4. Conclusions

In this study, a hybrid decision making approach for facility layout design is proposed. Due to the shortage of energy, energy relevant criterion is introduced as an important criterion and integrated with other traditional layout criteria in the process of layout decision making.

By using AHP, rational weights for decision criteria are easily made since its ability of quantification of experiences and pairwise comparison of decision criteria. Then due to the PROMETHEE's capability to reflect the way of human thinking which solves multiple contradictory problems with synthesizing preference, the proposed approach defines different preference functions and thresholds to evaluate different decision criteria according to their different features and magnitudes. Afterwards, the sensitivity analysis is carried out to study the influence of criteria weights fluctuation on the final ranking results. In addition, the greatest influencing criterion which has smallest stability interval and should be carefully treated in the process of layout design, is found.

Since the ambiguities are full of our real life, some criteria are qualitative or cannot be measured precisely. Therefore, in our future research the fuzzy theory will be integrated into our proposed approach. In addition, the sensitivity analysis of products demand fluctuation is also a valuable topic for layout designers and it will be also studied in our further research.

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